Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR–2008/13 **September 2008**

Survivability, Structures, and Materials Department
Technical Report

The Concept of Electrically Assisted Friction Stir Welding (EAFSW) and Application to the Processing of Various Metals

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14. ABSTRACT

This report introduces a novel variant of conventional friction stir welding (FSW). Since 1991, friction stir welding provides an alternative to arc welding as a metal joining method in numerous applications. In FSW, the heat required to soften the target metal is generated totally by the rotating friction of the tool which necessitates rather high downward (Z) operating force and often leads to relatively short tool life. In the proposed modification, an electric current is added through the tip which provides ohmic heating of the work piece in its vicinity. This additional contribution combines with the tool rotation to produce Electrically Assisted Friction Stir Welding (EAFSW) and reduces frictional forces required of the tool to produce softening of the work piece metal. This can result in reduced tool wear, lower applied Z force and potentially higher weld speed. The reduction in Z force requirement, in particular, might enable construction of a smaller, more portable FSW machine having similar weld capabilities as the current large units.

The machine modification/configuration is described. Experiments with various work piece metals and tool materials are discussed. Representative pictures of the resulting welds are presented. Finally, some conclusions regarding the possible scope and advantages of this new weld method are drawn.

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Administrative Information

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Executive Summary

This report introduces a novel variant of conventional friction stir welding (FSW). Since its inception in 1991, friction stir welding has provided an alternative to arc welding as a metal joining method in numerous applications. In the performance of FSW, the heat required to soften the target metal is generated totally by the rotating friction of the tool. This necessitates rather high downward (Z) operating force and often leads to relatively short tool life. In the modification proposed here, an electric current is added through the tip which provides ohmic heating of the work piece in its vicinity. This additional contribution combines with the tool rotation to produce Electrically Assisted Friction Stir Welding (EAFSW. The electrical heating reduces frictional forces required of the tool to produce softening of the work piece metal. This can result in reduced tool wear, lower applied Z force and potentially higher weld speed. The reduction in Z force requirement, in particular, might enable construction of a smaller, more portable FSW machine having similar weld capabilities as the current large units.

The machine modification/configuration is described. Experiments with various work piece metals and tool materials are discussed. Representative pictures of the resulting welds are presented. Finally, some conclusions regarding the possible scope and advantages of this new weld method are drawn.

Introduction

Welding is the preferred method of metal joining for most applications where permanent structural configuration is intended. The classic weld mechanism of arc or flame melting produces metal pooling along the weld line, which freezes to join the work piece. Application of electricity or combusting gas mixtures, the principal sources of heat, must often be applied with fluxes, filler metals, and inert cover gases. These processes have undergone many refinements over the years. In general, weld parameters must be closely controlled to obtain acceptable and reproducible weldments. Concerns in the heat affected zone (HAZ) include thermal stresses, oxidation and the like. Almost invariably, physical properties in the weld areas are degraded from those of the bulk metals.

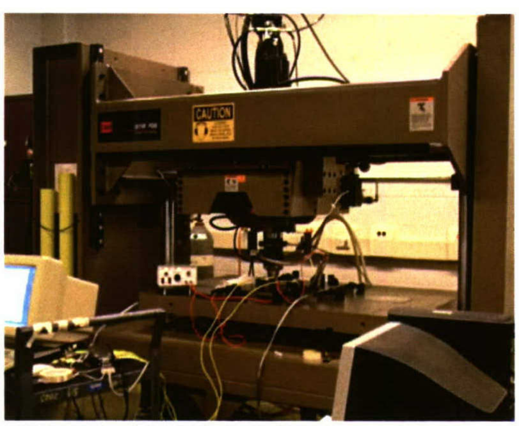
Since its advent in 1991, friction stir welding (FSW) has held promise of improved weld efficiency and physical properties of the product joint, among other advantages. Friction stir welding utilizes a rotating tip of appropriate material, which is forced against the butting edges of the weld pieces. The latter are placed firmly together and immobilized, usually by clamping.

The rotating tool produces heat by friction on the work piece softening the material and mixing it simultaneously. The process does not normally require filler metals and can often be successfully applied without an inert gas cover.

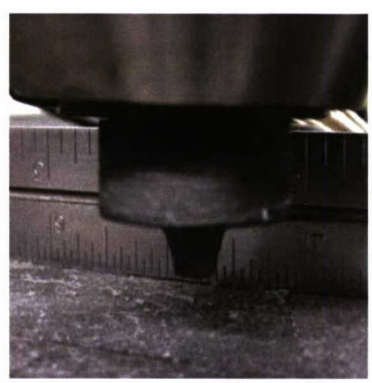
The FSW technique, however, despite its simplicity, has encountered a number of challenges to more widespread application. The relatively high downward force on the tool required to produce the heating required to initiate the weld virtually necessitates a large stationary machine for most applications. Figure 1 shows an example of such a machine and tool head. Here, the vertical force (Z-Load) and other parameters for welding the specified metals are noted. Other potential limitations of conventional FSW include low weld speed and significant tool wear. The electrically assisted friction stir welding (EAFSW) process modification may be able to address these concerns. Indeed, a modeling study of auxiliary heat input already has indicated potential benefit in these areas[1].

FSW of HSLA 65 and Type 304L

Processing Parameter	HSLA-65	304L
Spindle Speed (RPM)	850	850
Travel Speed (ipm)	6	2
Z-Load (lbs)	3500	3500
Tool Tilt (Degrees)	-3.5	-3.5



NSWCCD, MTS® ISTIR® PDS,
Intelligent Stir Welding FSW machine



W-25Re Tool
- Shoulder diameter of 0.9105"
- Pin length of 0.2725"

Figure 1. Commercial FSW Unit Showing also Tool Head and Weld Parameters

Experimental Setup

The EAFSW was achieved for the present purposes by modifying a standard vertical milling machine by installing a slip commutation ring on its spindle. An electrical brush system contacting this ring provided a means of applying current to the welding tip. Heavy flexible wiring was connected to the brush block and to a heavy duty spot welding unit. The unit was modified to run continuously, controlled by demand from a foot switch. Its current could be varied by use of an autotransformer on the input line. The current was measured with a standard resistor and digital volt meter. All the welding experiments were carried out using alternating current. The system was capable of a current maximum of about 700 amps. With addition of heavy wiring and air cooling, the unit could sustain about 650 amps for the duration of a typical weld without seriously overheating. This level of power was used in all the experiments discussed below. It is probably sufficient to test proof of concept for relatively thin work piece metals of ¼ inch or less. Thicker materials will require larger diameter tooling and at least several times as much current. Despite its current capability, the power supply is not a shock danger, as its operating potential is quite low (~4 volts). This should be generally true even for commercial units, which might eventually be manufactured.

The return current circuit lead was connected to a pair of copper bus bars running adjacent to the tool travel direction about 1inch from the tip on either side. The bars were first placed atop the work pieces, but later beneath them. The latter positioning will be more critical for thicker material, which will need significant heat assist in the lower body portion of the weld. Electrical insulation from the machine table was provided by layers of artificial mica, which possesses good thermal damage resistance and breakage durability. It also provides a good measure of thermal insulation, which allows greater heating efficiency of the weld region for a given applied current. The same mica material was employed beneath the clamping flanges to maintain the electrical isolation.

Figure 2 is a schematic representation of an FSW welding tip in motion with the electrical heating circuit path indicated. Figure 3 shows a close-up profile of an FSW tool with nomenclature. Figure 4 shows the modified mill shaft with copper slip ring and commutator brushes installed with weld tip in position. Figure 5 shows the system in welding configuration

with return circuit wire connected though the standard resistor (foreground) to the copper bus bars positioned on either side of the welding track. The artificial mica plates, which serve as both electrical and thermal insulators are visible below the work piece and under the clamps. In the case of the higher melting, harder metals (e.g. steel, titanium), it was determined that insertion of a stainless steel sheet underlay along the weld track was necessary

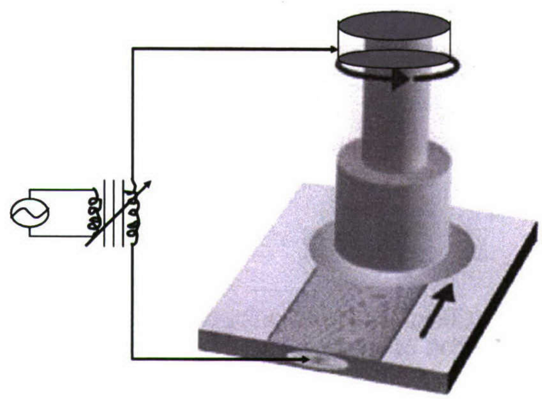


Figure 2. Schematic Illustration of Conventional Friction Stir Welding Tip with Auxiliary Electric Circuit for Supplemental Heating.

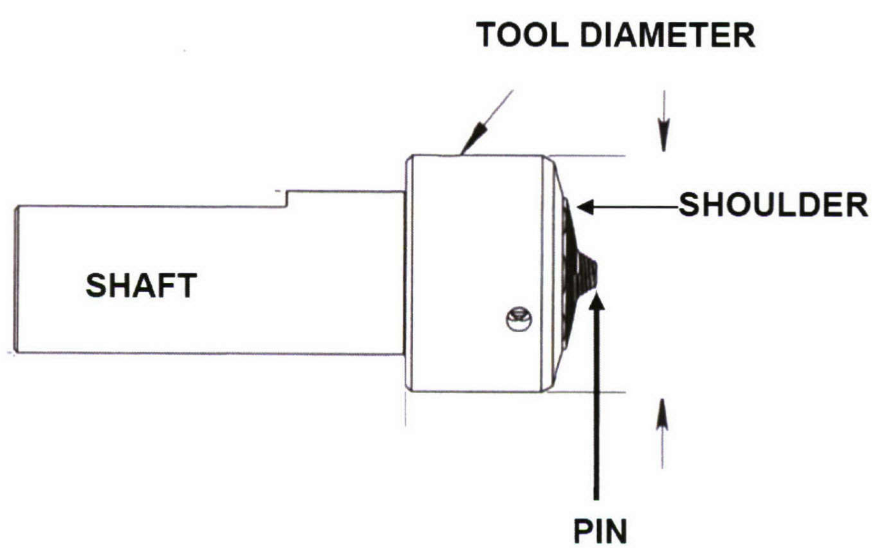


Figure 3. Close-up profile of FSW tool with nomenclature

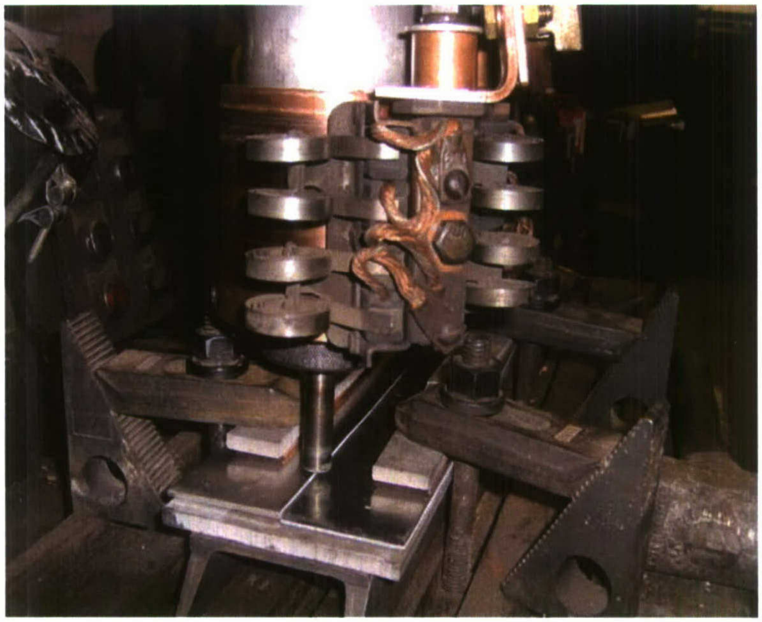


Figure 4. Mill Spindle with Slip Ring and Brush Assembly, Weld Tip is in Working Position.

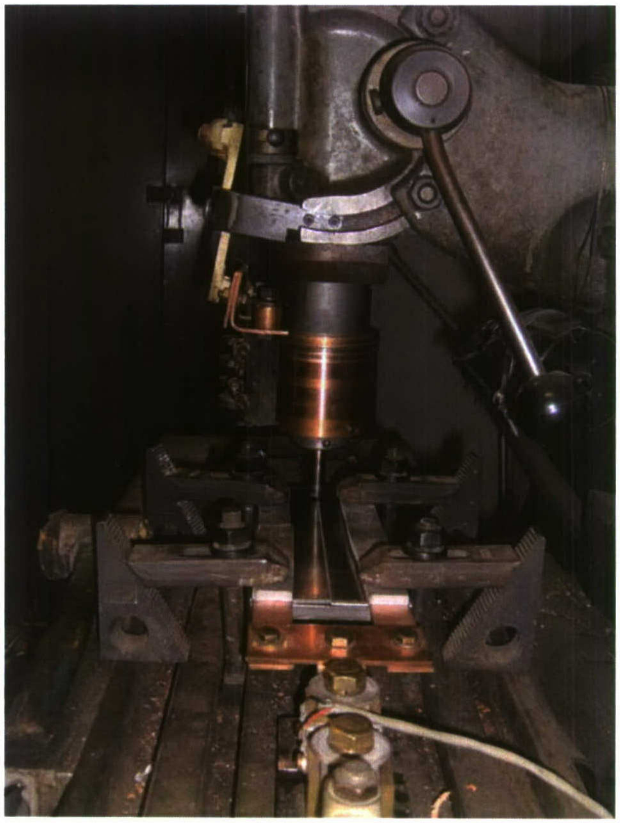


Figure 5. Mill Table with Standard Resistor for Current Measurement (foreground) and Insulating Artificial Mica Plates Beneath Work Piece and Clamps.

The vertical applied force (Z-force) was measured (roughly) by use of a common weighing scale in lieu of the unavailability of a precise load cell. This scale was set on the machine working table. Since the shaft spindle had been placed in fixed vertical position to accommodate the current ring assembly, the vertical force was exerted by manually raising the table against the tip. It was found that the maximum force able to be applied, before slippage of the raising assembly was about 260 lbs. Thus, all the electrically assisted welds reported here were carried out below this level. The table lift mechanism was (again roughly) calibrated using the aforementioned scale. Lateral travel was provided by the machine table motor. This could be preset for speeds up to 18 inches/min. This range is sufficient for any test welding experiments.

The EAFSW technique has several unique requirements for its successful application. In the case of arc welding, the return current wire often can be attached at any convenient point on the structure. This is the case because, once the arc is struck, the plasma assumes a high resistance compared to that of the structure itself and the external portions of the power circuit. A very large fraction of the electrical heating, therefore, takes place directly within the weld region, rapidly raising the local temperature beyond the melting point. This is not the case with EAFSW. Figure 6 illustrates various placements of the current return circuit wire. Relating to these possible placements, one must consider an important general electrical resistance characteristic of a planer homogeneous surface. That is the resistance of any square portion of the material (Ω/Υ) is equal to that of any other, regardless of size. Thus, the resistance of a square inch and that of a square foot are equal and so on. To illustrate this, Figure 6 shows representative squares of various sizes, depending upon the return wire placement.

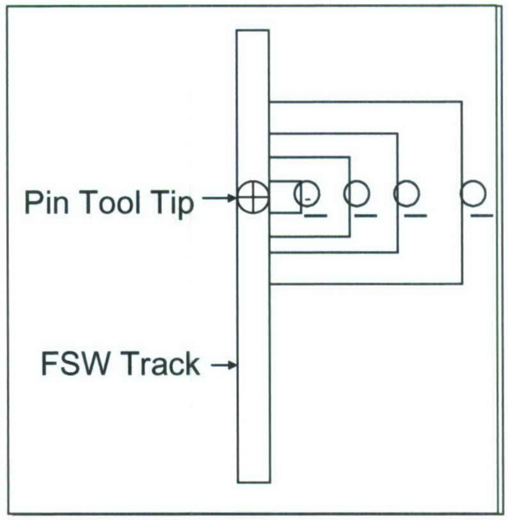


Figure 6: The Effect of Return Contact Position
on Resistive Heat Distribution

The direct ohmic heating of the work piece, I^2R_{wp}, is distributed throughout the total resistance area between the traveling tip and the return current wire. In view of the above discussion regarding Ω/Υ, the work piece will be subject to essentially identical total heat input for a given current, regardless of where the wire is connected. It follows, therefore, that maximizing the heating of the material in the weld vicinity will require the return conductor to remain close to the moving tip all along the weld path. In a table machine, such as the modified mill shown in Figure 5, this can be accomplished by using low resistance bus bars along the table paralleling the weld track. They are located preferably below the work piece so as to produce the heat from underneath and upward through the weld volume. In the case of a long weld table on a larger machine, maintenance of an optimal current configuration may necessitate the use of several return conductors connected along the length of the bus bars. In the case of machines run with a "self-reacting" tool configuration, it might be possible to attach the return current lead to the lower part of the assembly. Larger diameter tools and thicker work pieces will require higher currents than those achievable by the equipment described above to heat the larger stirred work piece volumes in these cases. The actual current required in a given application, of course, will depend upon the work piece thickness and resistivity. A second resistive heating contribution is provided by the heated tool itself (I^2R_{tool}) via thermal conduction across the tip/work piece boundary. This may be anticipated to be a relatively minor heating component over the weld duration.

The net heat input of all these contributions into the stirred volume, as the tool moves along, must not be allowed to produce melting of the work piece material in order to maintain the solid state nature of the weld process. The optimum heat input condition to minimize the vertical and lateral forces at a particular tool speed, while producing an acceptable weld, can be determined experimentally for a given material. Conceivably, as experience is gained with the process additional electrical heat input might be applied and the tool travel velocity increased proportionally to maintain a constant heat input/volume of the work piece. This would speed up the welding rate, potentially decreasing cost.

A portable hand-held type of FSW tool possibly could be developed. Use of such a tool would be limited to thin work pieces and probably to aluminum alloys. Again, the current return conductor must move along with the tip in close proximity. This could be done by designing a circular, spring loaded contact surrounding the spinning tip. This is illustrated in Figure 7.

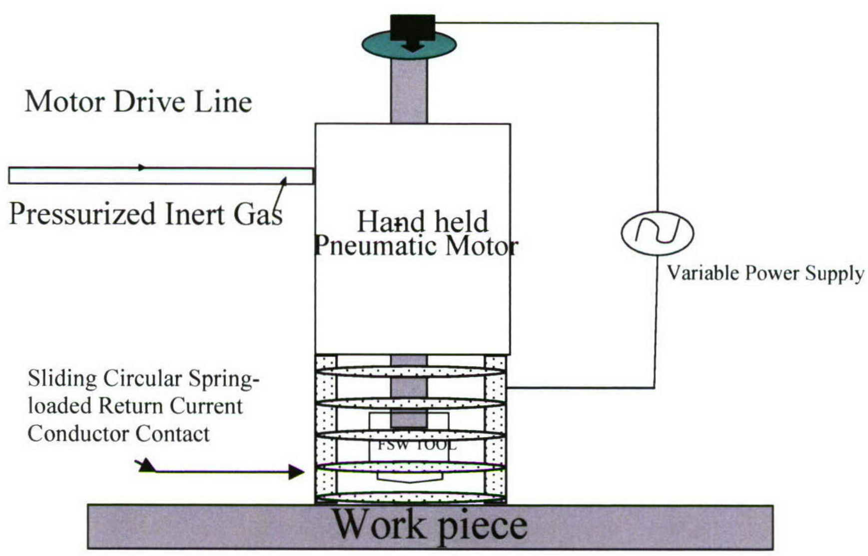


Figure 7. Concept Portable EAFSW Machine for Limited Applications

The choice of welding tool materials and geometry for EAFSW will prove somewhat challenging. In general, metal (alloys) exhibiting high melting temperature, good hardness at elevated temperature and oxidation resistance are suitable candidates. In addition, relatively low resistivity is desirable so that the tip itself does not run excessively hot. Initial experience showed that tip incandescence must be controlled. This is especially important in the case of

reactive metals, such as titanium. In the absence of inert cover gas, exposing the surface of these metals to too high a temperature will exacerbate oxidation problems. In addition, too high an operating temperature will soften the tip/pin, causing premature wear. Table 1 shows a list of candidate tool materials for consideration, or with which some experience has been gained. It is not an exhaustive list. Entries have been chosen for their potential to operate in the EAFSW mode. The refractory carbides, in particular, being closer to semiconductors, will heat rapidly with current application due to their high resistivities. They, therefore, will impart substantial conduction heating through the tool/work piece interface, which might be beneficial with certain metals. In any case, the tip heating characteristics must be matched to the metal work piece.

Table 1. Candidate Tool Materials for EAFSW

Material	Melting Point °C	Resistivity μ-ohm-cm	Comment
Cubic Boron Nitride	~3000	1900	Bronzes, steels (?); CBN very expensive, unavailable for this study
Molybdenum (TZM)	2617	5.2	Good for Al, some success with mild steel, bronze & Ti-6-4
Steel (SS, tool, mild)	~1540	10-70	Good for aluminum alloys
Tantalum	2996	12.5	Few tests with Ti & mild steel; somewhat expensive
Tungsten	3410	5.7	Useful for Al alloys; tip oxidation at elevated temperature
Titanium	1660	42	Too soft at elevated temperatures ; Al only
Vanadium	1890	25	Too soft at elevated temperatures
Zirconium	1852	25	Too soft at elevated temperatures
Tungsten/Rhenium	-	-	Unavailable to test, high temps, extremely expensive
Densimet	-	-	Tungsten/nickel alloy; tested; promise for mild steel/titanium
Tungsten carbide	2630	~80	Hardness ~9.1 Mohs Should test in compound tip config.
Titanium carbide	3100	180-250	Hardness ~9.6 Mohs Should test in compound tip config.
Silicon carbide	~2700	100-200	Hardness ~9.6 Mohs Should test in compound tip config.

In general, the smaller diameter tools used in the experiments reported here were configured as short working tips mounted in durable metal collars. This was necessary in order to circumvent their insufficient lateral strength at the ~2 inch operational length required by the head assembly. An additional advantage of the collar configuration is the reduction of the overall resistivity, and thus the heating, of the tool. This causes more heat to be generated, proportionally, in the work piece, where it is needed.

Materials and Testing

Aluminum

Most experience acquired at this writing has been with aluminum alloys. Welds were also eventually carried out on steel, bronze, copper/steel and titanium. Although some materials up to ½ inch thick were attempted, most welding and surface processing were restricted to material 1/8 in. to ¼ in-thick. The reason for this is primarily the current limitation of the power supply for electrical heating, which would need to be scaled up, along with the larger tool diameters required for thicker material. It was soon observed that operation in the electrically assisted mode apparently involves an apportioning of the heat energy between the tool tip and body of the work piece. Optimal division of this heating depends upon the characteristics of the target metal. In no case, however, was the ¾ inch maximum tip diameter accommodation of the mill head found to be a limitation for the present experiments. In practice, the largest tips for which the tip and work piece near vicinity could be raised to those required for true EAFSW welds with the present apparatus was limited to ½ inch.

A series of welds were carried out on available 1/8 in-thick Al 5083 plate. Figure 8 shows a representative weld track top view. The tool in its mounting collet is included in the picture. Figure 9 is a close-up photograph of this weld showing quite smooth surface quality. In general, aluminum alloys were found to be quite easily welded. This is not surprising, considering their relatively low melting temperature and even lower softening temperature. In fact, with the addition of a reasonable quantity of electrical heat to the work piece, the solid state stirring can proceed with much-reduced vertical force. As discussed below, applied forces of less than 100 lbs. were apparently sufficient to weld thin Al plate. This may make possible a hand-held unit of a configuration illustrated schematically above for weld repairs of thin Al alloy

plate. Return current sliding contact sets of appropriate geometry could be affixed for flat or curved plate or even right angle welding.

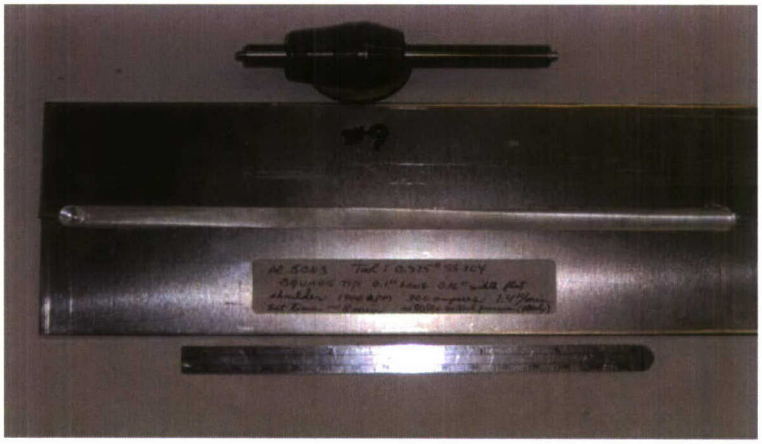


Figure 8. Electrically Assisted Friction Stir Weld (EAFSW) of 1/8-in Al 5083 Plate Showing also the 0.375-in diameter SS304 Tool. Z Force ~90 lbs (est.), 300 Amps Applied Current, 1300 rpm.

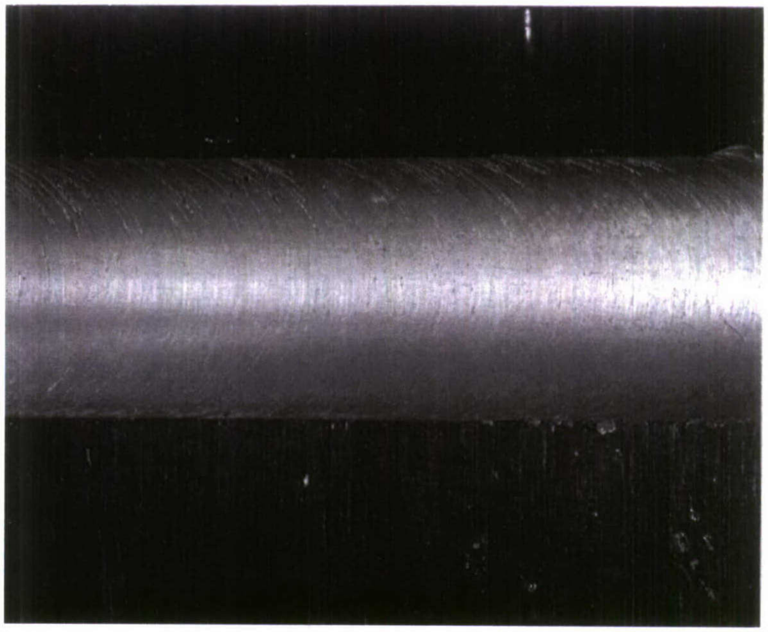


Figure 9. Close view of EAFSW weld of Figure 8. Mag. ~4X

Figures 10, 11, and 12 show cross-sectional micrographs of progressively more consolidated welds in this material (Al 5083). These were taken in montage form in order to bring out the weld detail and because of the limited lens field of view. The typical weld profiles of Figures 10 and 11 were performed with 3/8 in-diameter stainless steel tips. The first had a cylindrical "step" shape with flat shoulder, which left a considerable "worm-hole" down the center of the weld. This indicates significant non-uniform stirring of the softened material in the weld track, leading to incomplete weld closing. Figure 11 shows improved weld consolidation using a tool tip with a fluted geometry with sloping shoulder. Finally, Figure 12 shows the weld cross-section for the Al 5083 plate using a ½ in-diameter tool with a conical tip somewhat longer than the plate thickness with flat shoulder running at a decreased rotation speed of 900 rpm. There is apparently good consolidation in this weld. This indicates a probable reduction of the material flow stress, allowing more complete stirring of the softened region. The jagged portion at the bottom appears to be due to the mixing of some of the artificial mica under-lay into the weld. The tip length should be reduced slightly. It seems clear that with proper combination of tip geometry and rotational speed, good EAFSW welds can be produced in aluminum with an applied vertical force of the order of 100 lbs. This compares with forces of about 1000 lbs or so for conventional FSW welds in aluminum. With optimization of parameters, a higher weld speed also may be possible than is normally achieved with standard FSW.

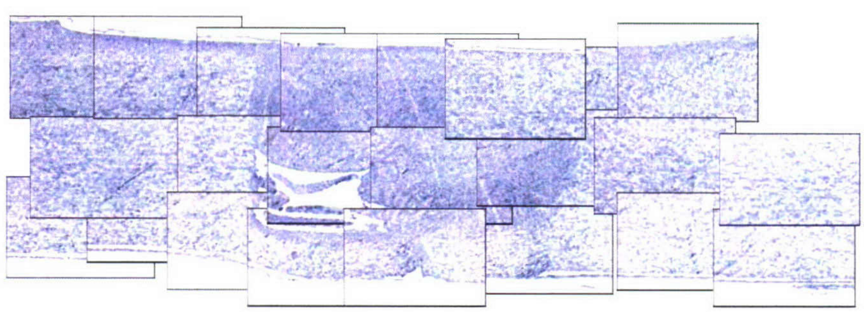


Figure 10. EAFSW weld cross-section in Al 5083 1/8 in-thick plate produced by 3/8 in-diameter SS 304 tool tip with square "step" geometry, applied current ~300 amperes, Z force ~ 90 lbs. 1300 RPM. Scale: ~ 10X

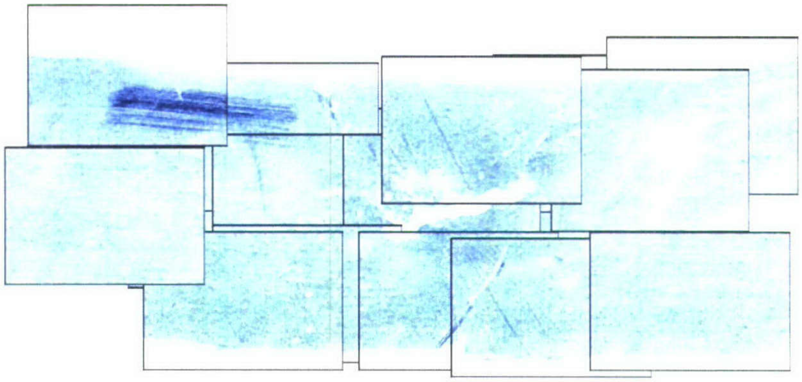


Figure 11. EAFSW weld cross-section of Al 5083 plate with similar weld parameters to those of Figure 10. Tip geometry was a truncated cone with sloping shoulder. Scale: ~10X

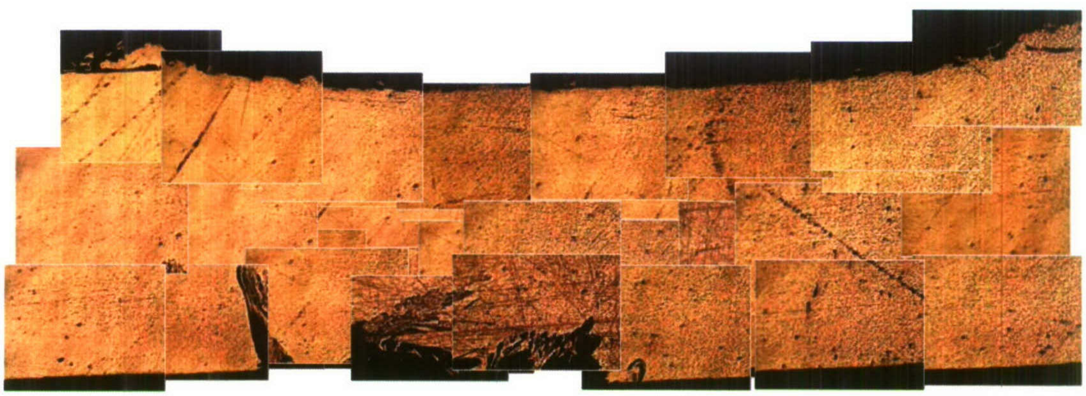


Figure 12. EAFSW weld cross-section of Al 5083 plate employing ½ in-diameter tool with conical tip at ~900 rpm. Scale: ~20X

Steel

A number of mild steel (1018) welds were attempted using the EAFSW apparatus. Steel obviously presents a far more demanding welding environment. Its relatively high melting temperature (~1540°C) poses a challenge. For friction stir welding to occur, the temperature within the work piece in the vicinity of the tool interface must be raised to the work piece softening temperature. This is typically within several hundred degrees of the melting temperature. Since metals, in general, begin to weaken significantly as they approach about 2/3 of their melt temperature, only those metals from Table 1 having melting temperatures well above 2000°C can be considered as prospective tool materials for steel. The entries for tungsten-

rhenium and cubic boron nitride (CBN) note that these are very expensive special fabrications. The carbides will require special fabrication techniques to produce tips, which may prove useful. The only readily available and comparatively inexpensive candidates are molybdenum (TZM) (m.p. 2617 ^{o}C) and tantalum (m.p. 2996^{o}C). The TZM designation refers to the addition of ~1% titanium and zirconium to pure molybdenum to provide some ductility (toughness). This property helps resist cracking of the material with variations in applied stress.

As the latter two metals were available on hand in rod form, they were tested with mild steel work pieces. Short rods of 3/8 in-diameter molybdenum (TZM) and ½ in-diameter Tantalum were machined to provide ~1/4 in-diameter cylindrical tips of ~1/8 in-depth with flat shoulders for the initial tests on 1/8 in-thick mild steel sheet. Again, the thin material was chosen for proof of concept because of the limited power capability of the system. Several welds were attempted with Ta tips with more or less similar results.

Figure 13 shows a first attempt weld on the steel plate. Serious deficiencies are evident. The plates are greatly deformed, the actual thickness of welded region is small with non-welded plate edges remaining as a crack extending well into the interior. The weld is not closed smoothly at the surface, but rather assumes the shape of a deep gouge. Finally, the bottom portion bulges downward, indicating insufficient strength of the underlay to prevent deformation at the weld base. Several more attempts with this tip led to the tentative conclusion that Ta may not be a suitable candidate for EAFSW of steel, not withstanding its high melting point. A white residue was observed on the tip and weld track. Investigation revealed the oxidation path to Ta_2O_5 (m.p. 1872^{o}C) as a colorless or white powder. Apparently, this oxide forms at the tip operation temperature. Ablation of the oxide produces rather rapid tip wear.

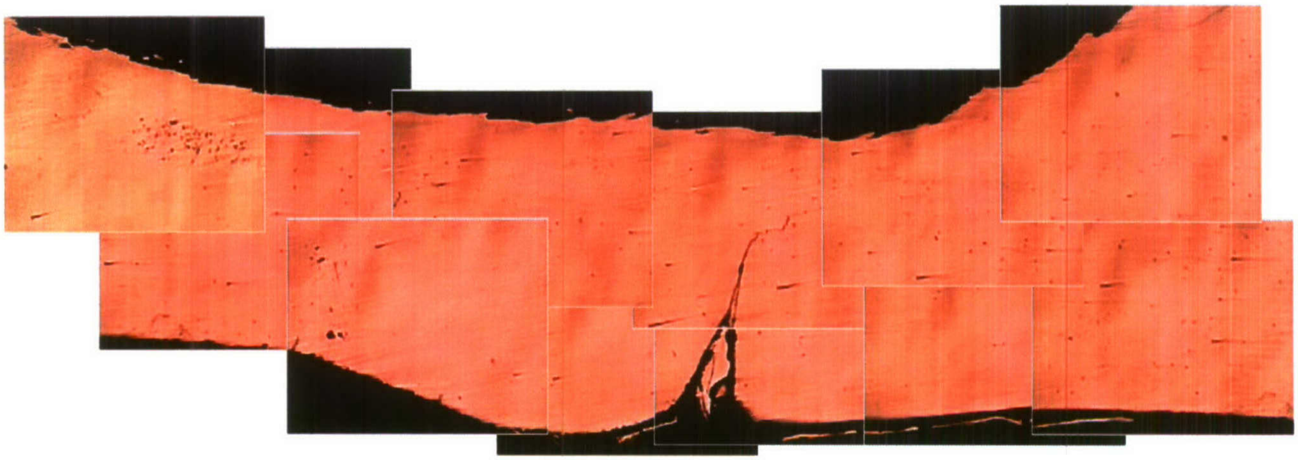


Figure 13. EAFSW weld cross-section of mild steel plates with ½-in Ta tool. Scale: ~15X

Molybdenum (TZM) was investigated subsequently as a possible weld tool. Previous experience with TZM molybdenum rods employed in stirring metal melts up to 1300°C have shown good service life in that application. The available TZM Mo rods were employed as tips in compound configuration with stainless steel collars to weld mild steel (1018). In the absence of the collar, the small diameter tips used in these experiments had insufficient shear strength to perform the weld.

Figure 14 shows a top view of a weld track in the steel and the Mo tip which produced it. Figure 15 is a closer view of this weld. The tip survived the 6-in. weld with apparently little wear. There was little indication of oxidation, even after several runs with the molybdenum tool. Although Mo has an oxide (MoO_3, sublimes 1153°C), apparently, its oxidation rate is slow compared to the test weld times.

A number of attempts were made to optimize the test weld configuration for steel. This, in fact, is still a work in progress. Figure 16 is a micrograph cross section of the Figure 14 weld. A very large "worm hole" is observed. Examination of this section indicates that the hole was largely caused by insufficient hardness of the mica underlay. This situation was remedied by substituting a strip of stainless steel for the mica sheet along the weld path. This strip was coated with a zirconia based mold wash "paint". This coating prevented shunting of the applied current through the stainless underlay strip and provided some thermal insulation. Thermal losses during welding, however, were increased over the original configuration with the mica underlay, a condition which may have contributed to the subsequent difficulty in closing the top of the weld.

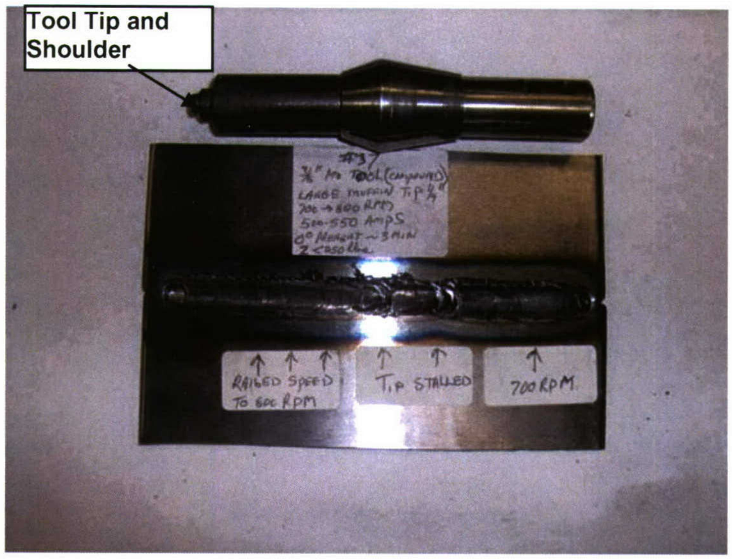


Figure 14. EAFSW weld in mild steel (1018) 1/8-in thick plate. The compound tool with 3/8 in-diameter Mo tool with Square profile pin and small flat shoulder is shown. The tool rotation was ~750 rpm, travel speed: 1.4-in/min, $Z_{load} < 250$ lbs. A current of about 550 amps was applied. Shown at ~1/2 scale.

Figure 15. Close top view of weld track of Figure 14. Shown approximately actual size.

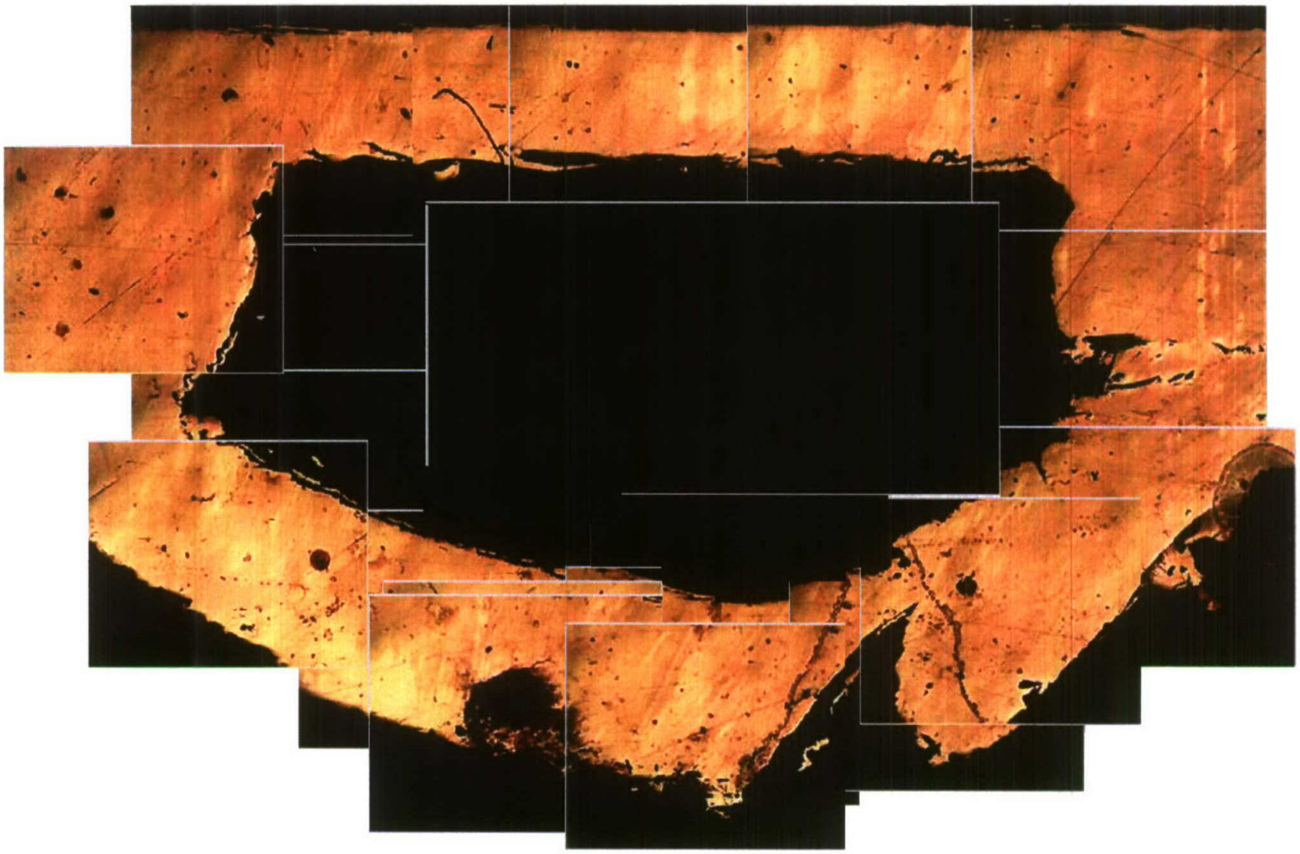


Figure 16. Cross-section of Figure 14 weld. Although weld top surface closed, insufficiently hard underlay material produces large open space "worm hole". Scale: ~20X

Figure 17 shows the effect of the hard underlay. The size of the worm hole is significantly reduced. There is, however, some incompleteness of the weld top closure. The weld was repeated with all equal parameters, except with the 3/16 in-diameter tip altered from square to somewhat conic cross-section. The resulting weld of Figure 18 shows the elimination of an obvious worm hole. The weld top, however, showed a pronounced furrow with ribbons of material ejected along the edge of the weld. Additional welds were made with the available 3/8-in. TZM molybdenum tips with little obvious improvement.

Tantalum ½ in-diameter tips also were tested, as noted above. In addition to its previously discussed behavior, however, a single exposure to incandescent temperature evidently causes marked weakening. Apparently, grain size grows rapidly with elevated temperature causing significantly increased brittleness. This brittleness manifested itself as a tendency to shear as the mill head advanced. Tantalum, therefore, was judged unsuitable for EAFSW tips, at least in the smaller diameters used in this effort. Finally, a few short rods of tungsten-cobalt-chromium alloy (densimet™) were obtained and fabricated into tips which were fitted to the stainless steel collars. These are being tested in EAFSW on the mild steel. Preliminary results have shown reasonably smooth metal surfaces in the weld tracks, indicating good stirring of the metal, although difficulty in closing the weld top still was encountered. This likely was due again to the square pin geometry and lack of sufficient electrical heating power in scale with the larger tool face diameter (3/4-inch). Without sufficient electrical heating, the larger tip shoulder could not be made to contact the work piece properly with the applied vertical force available. Again, with proper adjustment of parameters, acceptable welds should be possible.

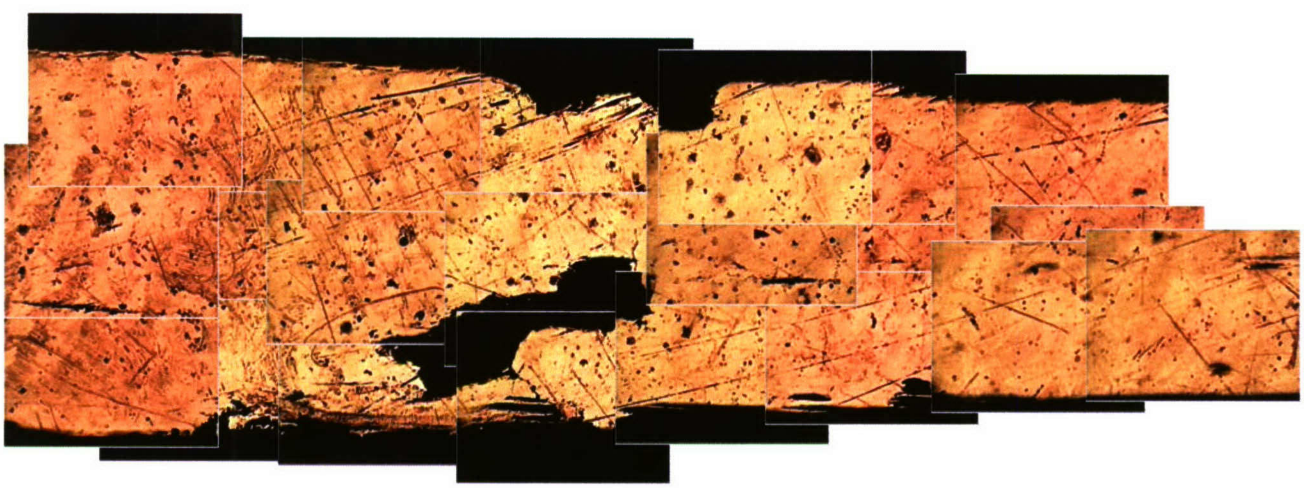


Figure 17. Cross-section of steel plate EAFSW weld having similar parameters as previous. The artificial mica backing plate beneath the weld track was replaced with a zirconia coated stainless steel plate. Scale: ~15X

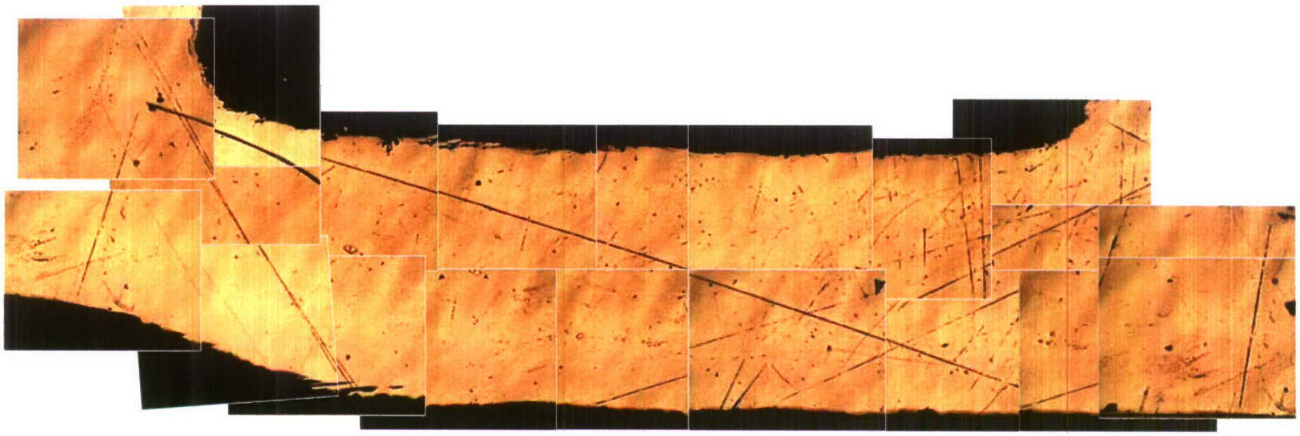


Figure 18. Cross-section of steel plate EAFSW weld using 3/8-in TZM molybdenum tool with 3/16-in conic tip at ~900 rpm. The "worm hole" has been eliminated, however a significant furrow remains. Scale: ~15X

Perhaps significant, the densimet tip was used several times on the mild steel and later on titanium with no readily visible wear. In its discussion of cobalt-chromium tungsten and molybdenum alloys, the Materials Handbook[3] notes superior wear characteristics at elevated temperature. It is stated that "Red hardness also makes these alloys more capable of resisting wear under almost all conditions where high local surface temperatures are developed." Also, since the material flow stress is decreased significantly by the bulk resistive heating in the tip vicinity as it tracks, a greater fraction of the tip kinetic energy can be dissipated in solid state mixing, rather than in frictional heating across the interface. The reduced demand for frictional heating on the tool thus may enable a densimet type alloy to be used for EAFSW of steels. This may allow a substantial cost reduction in the tooling versus the tungsten-rhenium alloy used in the present state of the art. This assertion, of course, remains to be proven by future investigation.

Titanium

Several welds were attempted in Ti-6Al-4V and Ti-commercially pure plate. Only 3/16 in-thick plates of the former and a single 3/16-in. plate of the latter, sliced from thicker plate stock, were available for these experiments. Figure 19 shows a weld in Ti-6-4 using a 3/8 in-TZM Mo tool. Several welds were attempted with similar results. The welded region is

shallow and the tool pin showed moderate wear. Some stirred, refined grain structure is evident in the welded region. There was only a small amount of visible oxidation. One explanation for the shallow weld condition is that the thickness of the plate exceeds the optimum for the small tool diameter. The plate thickness prevents electrical heating to a sufficient temperature, with the available current, to soften the titanium without overheating the tool. In other words, the tool diameter must be matched to the work piece thickness, in addition to optimizing other parameters. Electrical heating of the work piece volume in the tip vicinity should be maximized so that the reduced heat production of the rotating tip minimizes surface oxidation of the weld. These assertions must be verified by further testing

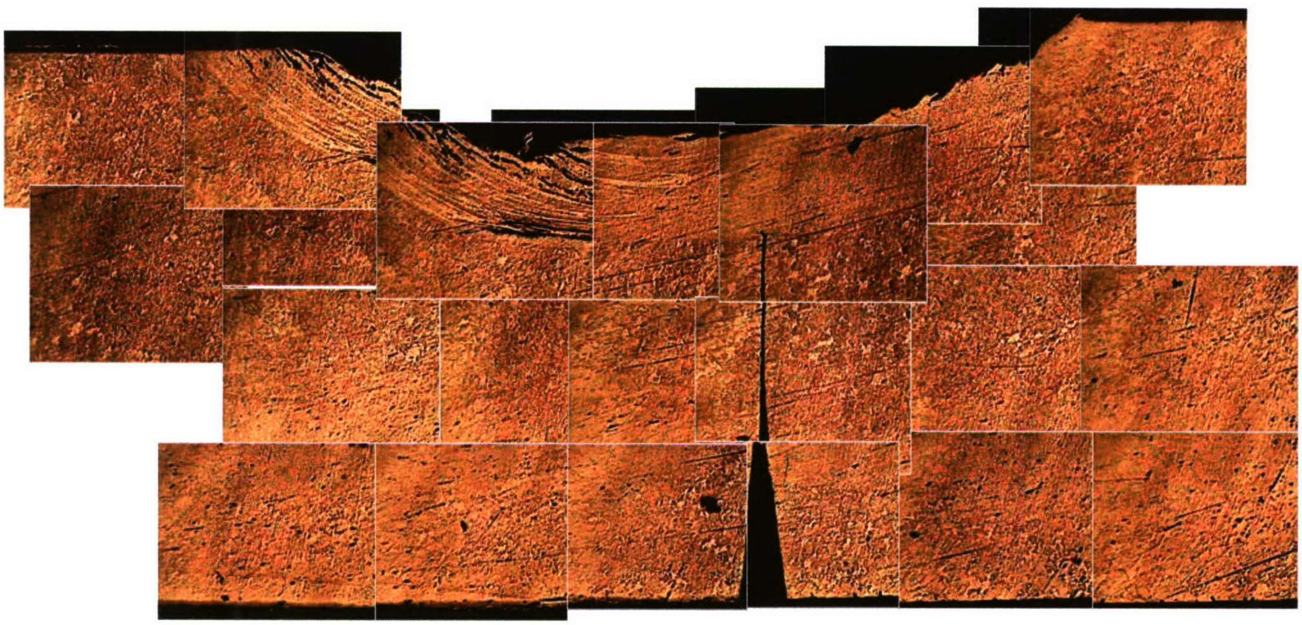


Figure 19. EAFSW weld cross-section in Titanium-6Al-4V 3/16 in-thick plate using TZM Mo 3/8 in-diameter rod with short square pin and flat shoulder. Rotational speed was about 300 rpm with about 550 amps applied. Scale: ~30X

Discussion

The pilot effort reported here is intended simply as proof of concept for electrically assisted friction stir welding. It is by no means an exhaustive investigation. In fact, the welding configuration and parameter range were constrained by the use of equipment and materials, which happened to be on hand. As already has been noted, methodic parametric studies must be performed to determine the overall feasibility and limitations/advantages of this approach for welding specific metals, thicknesses, tool materials and numerous other parameters. In order to do so, a test machine capable of a wide operating range of parameters should be employed. This can be accomplished either by modification of an existing commercial FSW machine or using a bottom-up design.

Conclusions

1. EAFSW, in which an adjustable electrical heating component is applied directly through the rotating tip to the work piece, appears to be a feasible augmentation to the traditional FSW approach, with some potential advantages over the latter.

2. A first attempt series of experiments has determined that a very significant reduction in Z axis force can be achieved with the electrical assist heating to that which is normally required for a given metal. This could lead to a physically smaller, possibly less expensive machine design, having similar weld capability of the current larger machines.

3. EAFSW may offer the possibility of a true hand held FSW device. As was discussed above, the necessity of completing the heating circuit in close proximity to the rotating tip of the work piece will present some design challenge in a hand-held machine. Such a unit probably will be restricted to use on thin plate, lower melting metals, notably aluminum alloys. In this case, the required vertical force lies within manual capability. Apparently higher forces may be required for other metals, although some tractable value may be achievable by adjusting the electrical heat input. In any event, such a portable device would be intended primarily for on-site repair/installation requiring few, relatively short welds.

4. EAFSW may reduce wear in tip materials currently used. This may be true, if sufficient heating can be produced in the work piece without overheating the tool itself. Examination by comparative testing is necessary.

5. The pilot work indicates that less expensive tip materials than those in current use might suffice in some applications.

6. Some increase in welding speed might be possible.

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